Reliability of Capacitors and Magnetic Components in Power Electronic Applications

Wang, Huai; Wang, Haoran; Shen, Zhan

Published in:
Proceeding of 11th International Conference on Integrated Power Electronics System (CIPS 2020)

Publication date:
2020

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Wang, H., Wang, H., & Shen, Z. (2020). Reliability of Capacitors and Magnetic Components in Power Electronic Applications. In *Proceeding of 11th International Conference on Integrated Power Electronics System (CIPS 2020)* (pp. 479-484). VDE Verlag GMBH. https://ieeexplore.ieee.org/document/9097729

Reliability of Capacitors and Magnetic Components in Power Electronic Applications

Prof, Huai Wang[a], Dr, Haoran Wang[a], and Mr, Zhan Shen[a]
[a]Aalborg University, Aalborg, Denmark

Abstract

This paper presents the wear out related reliability studies of capacitors and magnetic components used for power electronic converters. Accelerated lifetime testing, failure mechanisms, lifetime prediction and reliability design are presented based on the state-of-the-arts.

1 Introduction

Capacitors and magnetic components have become the requisite components and applied almost in every electronic circuits and energy conversion systems. As passive components, they are commonly used for filtering harmonics, storing and transferring energy, while inevitably contribute high percent of volume, power loss and degradation, and also failure rate for capacitors [1, 2, 3, 4].

With more and more stringent constraints brought by power electronics applications, capacitors and magnetic components encounter reliability aspect challenges: a) capacitors are one kind of the stand-out components in terms of failure rate in field operation of power electronic systems [5]; b) high-frequency pulses enabled by power semiconductor devices could lead to insulation aging and other uncertain failures for magnetic components, which has never been systematically studied before; c) the trends for high power density constraint the volume and thermal dissipation of magnetic components and capacitor banks, which could lead to overheating and parameter shifting [6, 7]; d) cost reduction pressure from global competition dictates minimum design margin of these components without undue risk; and e) they are to be exposed to more harsh environments (e.g., high ambient temperature, high humidity, etc.) in emerging applications.

To cope with these challenges, a lot of efforts are made to the reliability of capacitors, in terms of failure identification, lifetime testing and modeling, and reliability design. For magnetic components, there is mature research on the reliability of electrical machines and line-frequency high power transformers. The reliability of the insulator, magnetic cores, and windings are also investigated in literature. However, no systematic study of power electronic magnetics in the system-level. To the best of knowledge, no literature reviews the state-of-the-art on this topic. In this paper, an overview of the reliability of capacitors and magnetic components is provided in terms of lifetime testing, failure mechanisms, lifetime modeling and prediction, and reliability design. The challenges and opportunities for future research directions are finally addressed.

2 Accelerated Lifetime Testing

Capacitors and magnetic components can fail due to intrinsic and extrinsic factors, such as design defect, material wear-out, operating temperature, voltage, current, moisture, mechanical stress, and so on. Generally, their failures can be divided into catastrophic failures due to single-event overstress and wear-out failures due to the long-term degradation. Lifetime testing is used to identify and model long-term degradation behavior of the components.

An example of Accelerated Lifetime Testing (ALT) of DC-link capacitors is given in this part [8]. The purpose of this testing example is to study the degradation and lifetime of capacitors under critical stresses. The testing is performed by a capacitor testing system shown in Fig. 1(a), which is composed of a climatic chamber with a temperature range from -70 °C to 180 °C and a relative humidity level from 10 % to 95 % (within a certain temperature range), ripple current testers, and parameter characterization equipment. By applying the different critical stresses (e.g., voltage, current, temperature, and relative humidity level) for thousands of hours, the degradation behavior in terms of capacitance decrease and ESR increase can be measured for lifetime modeling [9].

The first degradation tests of planar transformers is reported in [10] and the corresponding tests are summarized in Fig. 1(b,c). This testing serves to observe the insulation performance and parameter shifts of power electronic magnetics under long-term thermal stress. Planar magnetics are stored at different temperature levels in the ALT. The inception voltage is measured by the partial discharge (PD) test to evaluate the performance of the insulator. The transformer parameters, e.g., the primary inductance and resistance, leakage inductance, short-circuit resistance, stray capacitance, and insulation resistance, are tested with an impedance analyzer. Based on the results at different degradation stages, the impact of the thermal aging to those parameters can be understood, which is used for the failure mechanisms analysis and lifetime modeling in the next step.

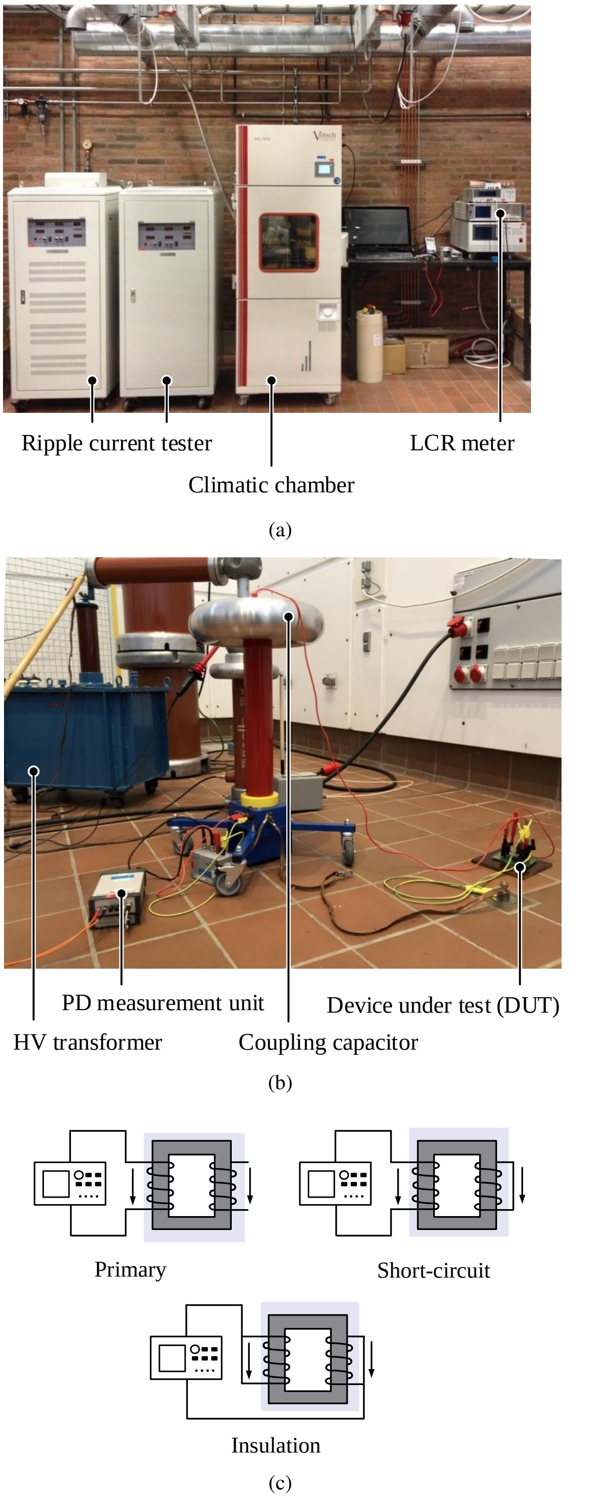


Figure 1 Accelerated lifetime testing experiments of capacitors and magnetics [8, 10]. (a) A capacitor degradation testing system. (b) The partial discharge experiment for insulation degradation tests. (c) The magnetics parameters degradation tests. The climatic chamber is omitted in (b,c).

3 Failure Mechanisms

Based on prior research results, Table 1 gives an overview of the failure modes, failure mechanisms, and corresponding critical stressors of the three types of capacitors [8].

Table 1 Overview of failure modes, critical failure mechanisms, and critical stressors of the three main types of DC-link capacitors (with emphasis on the ones relevant to the design and operation of power converters) [8].

Cap. type	**Failure modes**	**Critical failure mechanisms**
Al-Caps	Open circuit	Self-healing dielectric breakdown
		Disconnection of terminals
	Short circuit	Dielectric breakdown of oxide layer
	Wear-out: electrical parameter drift (C, ESR, tanδ, I_{LC}, R_p)	Electrolyte vaporization
		Electrochemical reaction (e.g., degradation of oxide layer, anode foil capacitance drop)
MPPF-Caps	Open circuit (typical)	Self-healing dielectric breakdown
		Connection instability by heat contraction of a dielectric film
		Reduction in electrode area caused by oxidation of evaporated metal due to moisture absorption
	Short circuit (with resistance)	Dielectric film breakdown
		Self-healing due to overcurrent
		Moisture absorption by film
	Wear out: electrical parameter drift (C, ESR, tanδ, I_{LC}, R_p)	Dielectric loss
MLC-Caps	Open circuit	Severe cracking (e.g., due to temperature excursions)
	Short circuit (typical)	Dielectric breakdown
		Cracking; damage to capacitor body
	Wear-out: electrical parameter drift (C, ESR, tanδ, I_{LC}, R_p)	Oxide vacancy migration; dielectric puncture; insulation degradation; micro-crack within ceramic

Electrolyte vaporization is the major wear-out mechanism of small size Aluminum Electrolytic Capacitors (Al-Caps) (e.g., snap-in type) due to their relatively high Equivalent Series Resistor (ESR) and limited heat dissipation surface [11]. A most important reliability feature of Metallized Polypropylene Film Capacitors (MPPF-Caps) is their self-healing capability. Initial dielectric breakdowns (e.g., due to overvoltage) at local weak points of a MPPF-Cap will be cleared, and the capacitor regains its full ability except for a negligible capacitance reduction. With the increase of these isolated weak points, the capacitance of the capacitor is gradually reduced to reach the end-of-life [12]. Unlike that of Al-Caps and MPPF-Caps, the Multi-layer Ceramic Capacitors (MLC-Caps) are expected to insignificant degradation at normal usage conditions. However, the failure of MLC-Caps may induce severe consequences to power converters due to the short circuit failure mode. The dominant failure causes of MLC-Caps are insulation degradation and flex cracking [13].

For magnetics in power electronics, a systematic overview of the failure mechanisms is missing. The research on the line-frequency power transformers and the electrical machines mainly focuses on the insulation system [15, 16]. The major stressors are temperature, moisture, and oxy-

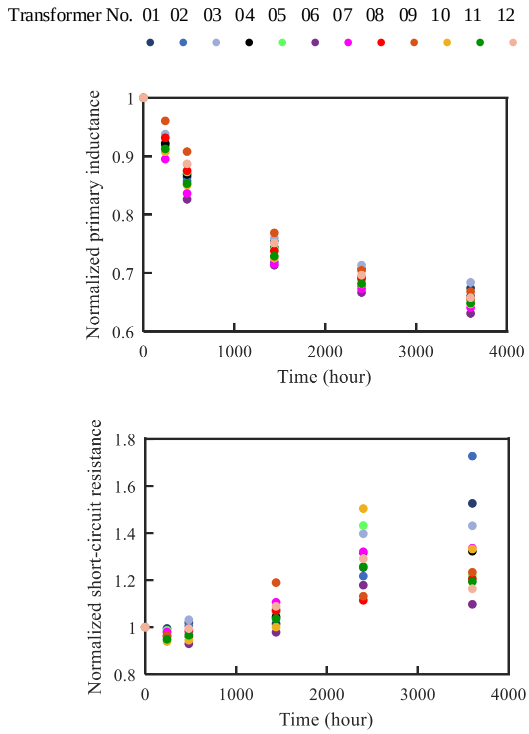


Figure 2 Selected degradation test results of planar transformers at 200 °C. The parameters are tested at 100 kHz. The transformer is with 27×30×10 mm dimension, 300 W rated power, ferrite core, PCB windings where 8 turns for primary and 4 turns for secondary, respectively. [14].

gen, while the critical failure mode is the breakdown of the insulation followed by the short-circuit or burning of the winding and the whole system. Among them, the thermal-related wear-out is considered as the primary degradation factor.

There are a few studies on the degradation of the magnetic core materials. The iron-based amorphous core grows the oxide layer, and the core loss density increases gradually during the wear-out [17]. There is the organic binder in the structure of the iron-power core. Therefore it is with low resistivity and increased loss density above 125 to 150 °C. The irreversible core loss increase heats up the core itself, and eventually causes thermal run-away in an inappropriate design [18]. The insulation tape/insulator used in power electronic magnetics are usually different from the insulation in power transformers and electrical machines. They are usually with Polyvinyl chloride (PVC), Vinyl, Polyimide, mica, etc. Their hydrolysis, thermo-oxidative, and long term electrical stress cause the wear-out failure and lose insulation function. The printed circuit board (PCB) is widely used in planar magnetics, which provides the board insulation between the copper traces. Its failure modes include cracks and the evaporation of solder masks under the stress of high temperature, thermal shock, vibration, humidity, etc [14, 19].

An early study on the degradation analysis of planar transformers is reported in [14]. During the long-term temperature storage test, the parameter shifts are observed, as in Fig. 2. The likely failure mechanisms are analyzed. The increase of the winding short-circuit resistance attributes to the oxidation of the copper layer; the decrease of the primary winding inductance and resistance are likely due to the expansion of the core glue or the aging of the core material; and the leakage inductance does not change significantly.

In conclusion, the following research of the failure mechanisms of the capacitors and magnetic components are clearly understood: a) dielectric loss or breakdown of capacitors; b) insulation degradation at line frequency and temperature stress; c) thermal aging curve of a few core materials, e.g., iron-based amorphous core, iron-power core; etc.

On the other hand, there are still research opportunities which have not yet been fully understood: a) the impact of different shape of electrical stress on the failure of capacitors; b) the failure mechanisms of capacitors under over stresses conditions; c) the core glue and its impact on the magnetic parameters; d) the insulation materials under the high-frequency excitation; e) the impact of PCB degradation on the planar magnetics; f) the lifetime indicator and end-of-life criteria of the power electronic magnetics under different failure mechanisms and application scenarios.

4 Lifetime Modeling

Lifetime models are essential for lifetime prediction and condition monitoring. The coefficients are extracted from the lifetime testing under scalable conditions [8].

The most widely used lifetime model for capacitors is shown below, which describes the influence of temperature and voltage stress:

$$L = L_0 \times (\frac{V}{V_0})^{-n} \times \exp[(\frac{E_a}{K_B})(\frac{1}{T} - \frac{1}{T_0})] \qquad (1)$$

where L and L_0 are the lifetime under the use condition and testing condition, respectively. V and V_0 are the voltage at use condition and test condition, respectively. T and T_0 are the temperature in Kelvin at use condition and test condition, respectively. E_a is the activation energy, K_B is Boltzmann's constant $8.62 \times 10^{-5} eV/K$, and n is the voltage stress exponent. Therefore, the values of E_a and n are the key parameters to be determined in the above model. For electrolytic capacitor and film capacitors, a simplified model from the above equation is popularly applied as follows [20]:

$$L = L_0 \times (\frac{V}{V_0})^{-n} \times 2^{\frac{T_0 - T}{10}} \qquad (2)$$

The model corresponds to a specific case of first equation when $E_a = 0.94eV$ and T_0 and T are substituted by $398K$. For MPPF-Caps, the exponent n is from around 7 to 9.4, which is used by leading capacitor manufacturers.

Equation (1) is also used for lifetime of the insulation under the electrical and thermal stress with different value of L_0, V_0, T_0, n, and E_a [22]. In power transformers, the insulation is normally considered as the weakest part, and its lifetime is regarded as the lifetime of the whole transformer. A more popular and simpler model from (1) only

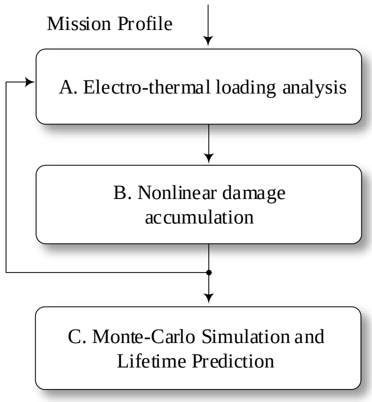


Figure 3 Mission profile based lifetime prediction procedure [21].

considers the impact of the temperature, and is recommended in the IEEE standard [23]

$$L = a \times \exp(\frac{b}{T}) \tag{3}$$

This equation is from the Arrhenius model, and a and b are constants for different insulation systems temperatures. Both (1) and (3) can also be applied to the insulation of the power electronic magnetics, however, the corresponding constants, e.g., L_0, V_0, T_0, n, E_a, a, and b should be re-determined. There are also other lifetime models considering the impact of the frequency on the insulation of the wire [24], the core degradation [14], etc.

Moreover, unlike capacitors using the capacitance value and ESR as lifetime indicator, power electronic magnetics are with more parameters. So there should be different lifetime models under different failure mechanisms and end-of-life criteria with different indicating parameters, which still needs further investigation.

5 Lifetime Prediction

For constant loading conditions, the lifetime model can be used directly for lifetime prediction by taking the electrical and thermal stresses into the model. For long-term mission profile, the variable loading conditions need be considered [3, 21]. The mission profile based lifetime prediction procedure is shown in Fig. 3. A mission profile is applied as the input, and the lifetime of the capacitor with a certain confidence level (e.g., 90 %) is the output. The procedure includes three major steps: electro-thermal loading analysis, damage accumulation, and Monte-carlo simulation based variation analysis, which are introduced below using capacitors as the example.

Thermal stress is one of the critical stressors for capacitors, resulting in the reduction of capacitance and the increase of ESR due to wear out. The current ripple and ambient temperature are the contributors to the internal thermal stress of the capacitor. For electrolytic capacitors, the dominant degradation mechanisms are electro-chemical reaction in the oxide layer and the electrolyte vaporization. Both factors lead to an increase in ESR over the operating life of a capacitor. Especially, the increase of capacitor power loss causes a higher operating temperature inside the capacitor. The hot-spot temperature of the capacitor, which is affected by the current stress and ambient temperature, is derived as

$$T_h = T_a + R_{ha} \times \sum_{i=1}^{n} [ESR(f_i) \times I_{rms}^2(f_i)] \tag{4}$$

where T_h is the hot-spot temperature, T_a is the ambient temperature, R_{ha} is the equivalent thermal resistance from hot-spot to ambient, $ESR(f_i)$ is the equivalent series resistance at frequency f_i, $I_{rms}(f_i)$ is the RMS value of the ripple current at frequency f_i. The hot-spot temperature T_h can then be estimated.

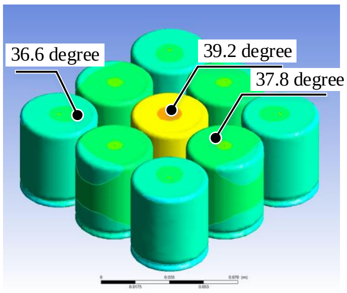
The linear and nonlinear accumulated damage model is developed to describe the real damage progress. The wear out of the capacitor is indicated by an increase of ESR. Damage is then defined as the ratio of instantaneous to final ESR growth. By accumulating the damage, the dynamical stresses are converted into static values for each type of temperature stress. Taking the accumulated damage into the lifetime model, the equivalent hot-spot temperature can be derived.

The application of the lifetime model results in fixed accumulated damage. It is far from reality since the capacitor parameter variations and the statistical properties of the lifetime model are ignored. In field operations, the time to end-of-life for the capacitors could vary within a range due to the tolerance in physical parameters and the difference in the experienced stresses. Therefore, a statistical approach based on Monte-carlo simulation is applied [21, 25]. The sensitivity of the lifetime to temperature tolerance-related parameters can be evaluated individually or collectively. Finally, the distribution of the end-of-life of the capacitors can be obtained, allowing a lifetime analysis with a specified confidence level.

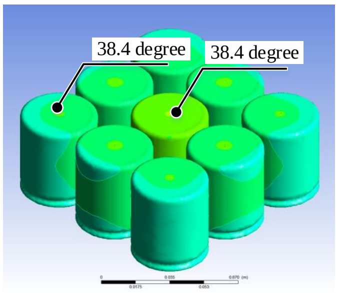
The lifetime prediction of the magnetics under the long-term mission profile follows similar steps as capacitors. However, several aspects are different, which require further investigation: 1) the lifetime model of the power electronic magnetics under different stresses needs further study and validation; 2) the accumulated damage model for the power electronic magnetics according to the real damage progress is still missing, etc.

6 Reliability-oriented Design and Optimization

From the lifetime model, it can be seen that the rated lifetime, voltage stress, and thermal stress are the key factors affecting the capacitor lifetime. Therefore, the reliability of capacitors can be optimized by choosing ones with different rated parameters and the actual stresses [26]. For example, in a capacitor bank with multiple capacitors, the thermal coupling among capacitors varies with physical locations. The electro-thermal stresses among individual capacitors could be different. By optimizing the rated parameters or actual stresses of the individual capacitor, it is possible to balance the temperature as well as lifetime in



(a) Without thermal loading re-distribution method.



(b) With thermal loading re-distribution method.

Figure 4 Simulation results of a capacitor bank without and with the thermal loading redistribution solution [26]. (a) conventional solution with 470 μF $\times$ 6 capacitors, and (b) thermal loading redistribution solution with 680 μF $\times$ 4, 560 μF $\times$ 4 and 390 μF $\times$ 1 capacitors.

a bank. Then, no one capacitor would fail earlier than the others [7].

One way to match the lifetime of the individual capacitors is by selecting capacitors with different rated lifetime to configure the capacitor bank. If the lifetime of the individual capacitor can be the same by optimizing the rated lifetime, no one capacitor would fail earlier than the others. Therefore, the optimization target of the rated lifetime allocation method is defined as to minimize the lifetime difference among capacitors.

Another way to achieve the same lifetime is by balancing the thermal stress distribution. Power loss is the source for the thermal stress, which is determined by the current spectrum and ESR of capacitors. The current flowing through individual capacitor depends on the capacitance (or impedance at the specified frequency) of each, because of the current sharing among capacitors. By changing the capacitance of the individual capacitor, the corresponding heat injection will change accordingly as well as the temperature distribution. When the temperature difference among capacitors is zero, the capacitance for the individual capacitor in a bank can be acquired for even temperature distribution to reduce the lifetime mismatch.

The reliability-oriented design of power electronic magnetics components is a further research step of the conventional electromagnetic-thermal multi-physics design. This future work follows after the system-level lifetime modeling and prediction of power electronic magnetics. The reliability-oriented design can help the designers not simply follow the design restrictions, e.g., the electrical strength and thermal limit, but rather adjust those restrictions in order to fulfill the lifetime requirements. On the other hand, magnetic components are normally regarded as reliable compared with other devices in power electronics. Therefore, a minimum design margin of magnetic components can be reached to reduce the cost further and fulfill the requirements of the service life.

7 Summary

This paper presents the state-of-the-art research on the reliability of capacitors and magnetic components in power electronic applications. It can be seen that:
1) reliability of capacitors has been studied extensively, but more study in terms of the applications dependent evaluation, design, and optimization are necessary;
2) reliability of magnetic components is essential in high frequency, high density, low cost, or severe applications, and the parameter shifts or insulation breakdown are likely to be the major degradation and failure modes;
3) existing research focus on the reliability of cores, insulation, and wire, and a systematic study on the system-level of magnetics is still missing;
4) there are research opportunities on the reliability for magnetics, including degradation and failure mechanism, lifetime modeling and prediction, and reliability-oriented design and optimization.

8 Literature

[1] F. Zare, H. Soltani, D. Kumar, P. Davari, H. A. M. Delpino, and F. Blaabjerg, "Harmonic emissions of three-phase diode rectifiers in distribution networks," *IEEE Access*, vol. 5, pp. 2819–2833, 2017.

[2] D. Neumayr, D. Bortis, and J. W. Kolar, "Ultra-compact power pulsation buffer for single-phase dc/ac converter systems," in *Proc. IEEE ECCE Asia*, 2016, pp. 2732–2741.

[3] H. Wang, P. Davari, H. Wang, D. Kumar, F. Zare, and F. Blaabjerg, "Lifetime benchmarking of two dc-link passive filtering configurations in adjustable speed drives," in *Proc. IEEE APEC*, 2018, pp. 228–233.

[4] R. De Doncker, D. Divan, and M. Kheraluwala, "A three-phase soft-switched high-power-density dc/dc converter for high-power applications," *IEEE Trans. Ind. Appl.*, vol. 27, no. 1, pp. 63–73, Jan. 1991.

[5] H. Wang, M. Liserre, F. Blaabjerg, P. de Place Rimmen, J. B. Jacobsen, T. Kvisgaard, and J. Landkildehus, "Transitioning to physics-of-failure as a reliability driver in power electronics," *IEEE Trans. Emerg. Sel. Topics Power Electron.*, vol. 2, no. 1, pp. 97–114, Mar. 2014.

[6] J. Rajmond and P. Dan, "Thermal modeling of through hole capacitors," in *Proc. IEEE SIITME*, 2012, pp. 227–232.

[7] H. Wang and H. Wang, "Reliability evaluation and optimization of capacitor bank," in *Proc. IEEE ECCE*, 2018, pp. 7386–7390.

[8] H. Wang and F. Blaabjerg, "Reliability of capac-

itors for dc-link applications in power electronic converters-an overview," *IEEE Trans. Ind. Appl.*, vol. 50, no. 5, pp. 3569–3578, Sep. 2014.

[9] M. L. Gasperi, "Life prediction model for aluminum electrolytic capacitors," in *Proc. IEEE ISIE*, 1996, pp. 1347–1351.

[10] Z. Shen, Q. Wang, Y. Shen, and H. Wang, "First observations in degradation testing of planar magnetics," in *Proc. IEEE APEC*, 2019, pp. 1436–1443.

[11] R. Alwitt and R. Hills, "The chemistry of failure of aluminum electrolytic capacitors," *IEEE Trans. Parts, Mater., Packag.*, vol. 1, no. 2, pp. 28–34, Sep. 1965.

[12] R. W. Brown, "Linking corrosion and catastrophic failure in low-power metallized polypropylene capacitors," *IEEE Trans. Device Mater. Rel.*, vol. 6, no. 2, pp. 326–333, Jun. 2006.

[13] W. Minford, "Accelerated life testing and reliability of high k multilayer ceramic capacitors," *IEEE Trans. Compon., Hybrids, Manuf. Technol.*, vol. 5, no. 3, pp. 297–300, Sep. 1982.

[14] Z. Shen, Q. Wang, and H. Wang, "Degradation analysis of planar magnetics," in *Proc. IEEE APEC, accepted*, 2020.

[15] Q. Zhong, "Power transformer end-of-life modelling: Linking statistics with physical ageing," Ph.D. dissertation, Manchester, UK: The University of Manchester, 2012.

[16] M. Kaufhold, H. Aninger, M. Berth, J. Speck, and M. Eberhardt, "Electrical stress and failure mechanism of the winding insulation in pwm-inverter-fed low-voltage induction motors," *IEEE Trans Ind. Electron.*, vol. 47, no. 2, pp. 396–402, Apr. 2000.

[17] T. Matsmura, K. Nagayama, S. Hagimura, and M. Higaki, "Long term reliability of iron-based amorphous alloy cores for oil-immersed transformer," *IEEE Trans. Magn.*, vol. 26, no. 5, pp. 1993–1995, Sep. 1990.

[18] Micrometals, "Core loss increase due to thermal aging in iron powder cores," https://www.micrometals.com, Tech. Rep., 2007.

[19] S. Akbari, A. Lövberg, P.-E. Tegehall, K. Brinkfeldt, and D. Andersson, "Effect of pcb cracks on thermal cycling reliability of passive microelectronic components with single-grained solder joints," *Microelectron. Reliab.*, vol. 93, pp. 61–71, Jan. 2019.

[20] S. G. Parler Jr and P. C. Dubilier, "Deriving life multipliers for electrolytic capacitors," *Proc. IEEE Power Electron. Soc. Newsletter*, vol. 16, no. 1, pp. 11–12, 2004.

[21] H. Wang, P. Davari, H. Wang, D. Kumar, F. Zare, and F. Blaabjerg, "Lifetime estimation of dc-link capacitors in adjustable speed drives under grid voltage unbalances," *IEEE Trans. Power Electron.*, vol. 34, no. 5, pp. 4064–4078, May 2019.

[22] L. Simoni, "General equation of the decline in the electric strength for combined thermal and electrical stresses," *IEEE Trans. Electr. Insul.*, vol. EI-19, no. 1, pp. 45–52, Feb. 1984.

[23] IEEE Power and Energy Society, *IEEE Guide for Loading Dry-Type Distribution and Power Transformers*, Jan. 2014.

[24] S. Grzybowski, N. Kota, H. Voltage, and Laboratory, "Lifetime characteristics of magnet wires under multistress conditions," in *Annu. Rpt. IEEE CEIDP*, 2005, pp. 605–608.

[25] P. D. Reigosa, H. Wang, Y. Yang, and F. Blaabjerg, "Prediction of bond wire fatigue of igbts in a pv inverter under a long-term operation," *IEEE Trans. Power Electron.*, vol. 31, no. 10, pp. 7171–7182, Oct. 2016.

[26] H. Wang and H. Wang, "Capacitive dc links in power electronic systems-reliability and circuit design," *Chinese J. Electr. Eng.*, vol. 4, no. 3, pp. 29–36, Sep. 2018.